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COMPRESSION TEST SIMULATION OF THICK-SECTION COMPOSITE MATERIALS

TZI-KANG CHEN
MECHANICS AND STRUCTURES BRANCH

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ABSTRACT

An improved compression test concept for thick-section composite materials based on a stress analysis simulation study is presented. An end loading method involving specimen support by a locked hemispherical seat was identified as the most desirable. The results showed that this method could substantially reduce the stress variation due to specimen imperfection and loading eccentricity. Compression test methods are analyzed using a finite element methodology. Limitations of the test methods are identified with respect to their ability to obtain the desired uniform stress field. The end loading method proved to be superior to the side loading method for the thick-section composite material. The frictional forces introduced by the end loading method can reduce local failure at the specimen end. The zone of end effects on the stress distribution was obtained for the composite material.

CONTENTS

INTRODUCTION

Increasing use of thick-section composite materials structures has resulted in an obvious need for the materials' mechanical properties. In compressive loading the mechanical properties are usually difficult to measure accurately. Different failure modes often occur within a specimen and among different specimens resulting in large variations in the test results.

Currently, there appears to be no universally accepted standard for compressive testing of composite materials. The test methods depend on properties of matrix, the fibers and their interface, strength and anisotropy of the composite, stacking sequence of the lamina (unidirectional, quasi-isotropic, symmetric, or unsymmetric), and the geometrical shape of the specimen (length, width, thickness, and slenderness ratio). Recently, Schoeppner and Sierakowski[1] evaluated more than 20 different composite compression test methods currently being used by test engineers. Some of the methods required complex testing techniques involving elaborate fixtures and specimen configurations. It was shown by Gedney[2] there can be as much as a 30% difference in compression test results depending on the test method. Camponeschi[3] recently evaluated a number of compressive test methods which resulted in his development of a test fixture for thick-section composite materials.

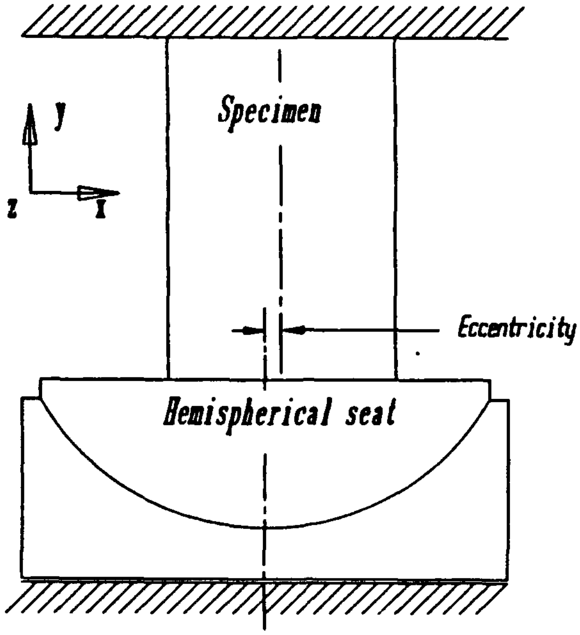
The current compression test methods are of two basic types: end loading and side loading of the specimen (see Figures 1a and 1b). The side loading method is generally used for thin-section composite materials. The side loading fixture constrains the ends of the specimen thus preventing Euler buckling and local failure at the ends. However, the side loading fixture has difficulty in applying a sufficient compressive load on the thick-section specimen since the frictional forces applied on the side surfaces of the tab end are limited by both the surface conditions and the strength of the tab.

The end loading method is usually considered undesirable for thin-section composite material by most test engineers. The method can result in either Euler buckling failure or local failure such as end brooming and specimen splitting. The measured strength is usually less accurate (lower) than that obtained from the side loading method. However, for thick-section composite material the buckling failure mode usually does not exist. Therefore, the end loading method can be considered as a desirable alternative to the side loading method if local failure can be prevented.

There are a number of advantages in using the end loading method for compression testing of thick composite. The fixture is simple and economical to make. The specimen is inexpensive to fabricate and can be easily mounted and tested. The deformation field in the specimen is much more uniform than that obtained from the side loading method. The fixture can easily be incorporated into environmental testing.

In composite specimen the decay length of the nonuniform stress distribution at the end is significantly greater than that for the isotropic material.[4,5] In order to obtain a uniform stress field it is, therefore, necessary to study how the end effect is affected by anisotropy.

1. SCHOEPPNER, G. A., and SIERAKOWSKI, R. L. *Review of Test Methods for Organic Matrix Composites*. Journal of Composites Technology & Research v. 12, no. 1, Spring 1990, p. 3-12.
2. GEDNEY, C. C., PASCUAL, C. R., and KOLKAILAH, F. A. *Comparison of ASTM Standard Compression Test Methods of Graphite/Epoxy Composite Specimens*. Advanced Materials Technology 1987, 32nd International SAMPE Symposium, Anaheim, CA, 1987, p. 1015-1024.
3. CAMPONESCHI, E. T., Jr. *Compression Response of Thick-Section Composite Materials*. Report DTRC SME-90-60, David Taylor Research Center, Bethesda, MD, October 1990.
4. CHOI, I., HORGAN, C. O. *Saint-Venant's Principle and End Effects in Anisotropic Elasticity*. Journal of Applied Mechanics, v. 44, 1977, p. 424-430.
5. HORGAN, C. O. *Recent Developments Concerning Saint-Venant's Principle: An Update*. Applied Mechanics Review, v. 42, no. 11, November 1989, p. 295-303.



1a. End loading method

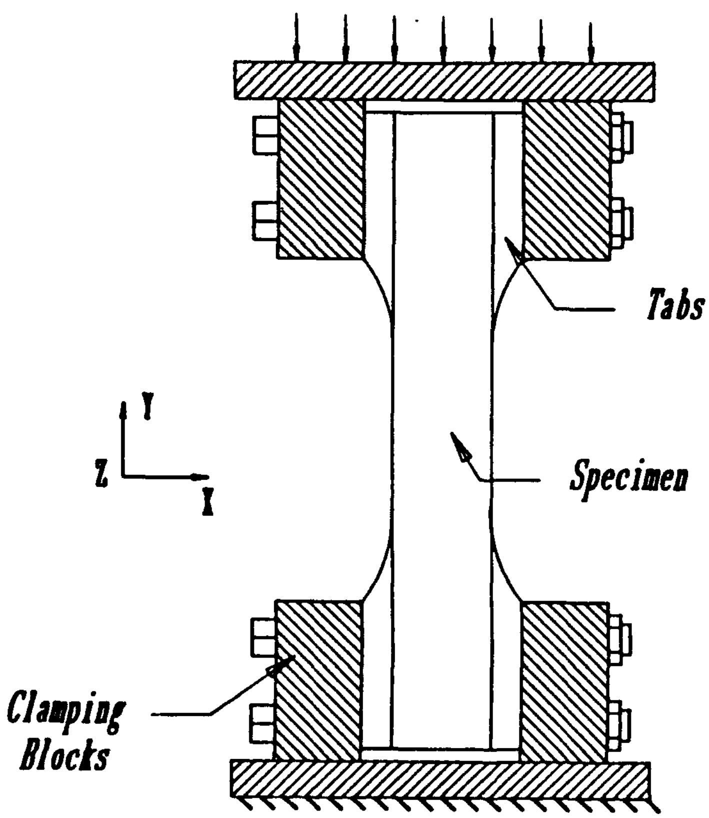


Figure 1. Sketch of the compression test.

The effects of the frictional force between the specimen ends and fixture platens in the end loading method can also influence the test results. Experimental results[1-3,6] showed that the strength measurements for composite materials will increase when a large frictional force exists due to suppression of local end failure.

In the end loading method the geometric imperfections of the specimen ends and the fixture platens can introduce a stress concentration. This can cause an inaccurate measured strength value. In order to eliminate these problems, test engineers have introduced a method involving a lubricated hemispherical seat which is placed between the testing machine and specimen (see Figure 1a). Unfortunately, the seat may tilt in the testing process. This is a result of a bending moment introduced from either loading eccentricity or unsymmetric composite.

This report involves an analytic study which examines the effect of using a locked hemispherical seat in order to eliminate the tilting action of the seat.

OBJECTIVES

The following objectives define the overall effort in the evaluation of compressive test methods for thick-section composite material:

- Determine the effects of loading eccentricity on the specimen using the hemispherical seat in the end loading compression test.
- Determine the errors in the measured stress introduced by the specimen imperfection using the end loading methods (with and without locked hemispherical seat).
- Examine the effects of frictional forces between specimen and the test fixture.
- Determine the end effects from the side and end loading compression test methods in order to aid in identifying the appropriate test method.

FINITE ELEMENT MODELING

In order to evaluate the compressive testing methods, finite element (FE) models were developed. An end loaded specimen (0.75" x 0.75" x 1.5") without side support was used in the FE analysis (see Figure 1a). This type of the specimen is similar to that used by Fazli et al.[7] The ABAQUS finite element program[8] was used in obtaining the analytic results. Both two- and three-dimensional FE analyses were carried out in order to determine the stress state in an unsymmetrical specimen. In the three-dimensional model 600 isoparametric quadratic elements were used in order to represent a 10 crossply laminate ($[0,90]_5$). In the two-dimensional model, 800 isoparametric quadratic elements were used for analyzing a 40 crossply laminate composite. All of the computations were performed using the orthotropic elasticity theory where the nonlinear geometric condition was assumed. In the analysis, convergence studies were conducted on the nodal force with an acceptable tolerance of ± 1 lb. The automatic loading step procedure provided by the ABAQUS code was used in the deformation analysis; approximately 20 steps were used for a compressive strain of 1.5%.

6. TARNOPOL'SKII, YU. M., KINCIS, T. *Static Test Methods for Composites*. Van Nostrand Reinhold Company, New York, NY, 1985.
7. FAZLI, J., GOEKE, E., and NUNES, J. *Characterization of Thick Glass Reinforced Composites*. U.S. Army Materials Technology Laboratory, technical report in process.
8. ABAQUS Users Manual, Hibbitt Karlsson and Sorenson, Inc., Providence, RI, 1989.

In the two-dimensional analysis interface elements were applied between the crosshead and specimen in order to simulate the friction conditions. Various coefficients of friction were selected in order to represent different surface and testing conditions.

A subroutine was developed to simulate the boundary condition at the bottom of the specimen (the tiltable hemispherical seat). The boundary condition was represented by a rigid line (top of the seat) which is constrained so that it would rotate only about a point (the center of the seat). The distance between the center of the hemispherical seat and center of the specimen represents the loading eccentricity (see Figure 1a).

The material used in the analysis was a glass fabric polyester matrix composite (SP-250-S29). The material properties of the composite were obtained from end loading compression test results[7] and material supplier's compression data (3M Aerospace Materials Department). The elastic stiffness matrix of the unidirectional fiber composite (0^{o}) is shown as follows:

$$C = \left| \begin{array}{cccccc} 7.1837 & 0.7379 & 0.7379 & 0 & 0 & 0 \\ & 2.0958 & 0.7424 & 0 & 0 & 0 \\ & & 2.0958 & 0 & 0 & 0 \\ & & & 0.8 & 0 & 0 \\ & sym & & & 0.5 & 0 \\ & & & & & 0.8 \end{array} \right| \times 10^{6}\ (psi)$$

The stresses and strains obtained from the three-dimensional analysis were compared with the two-dimensional results. There was no significant difference in the results, therefore, the results from two-dimensional analysis are presented in this paper.

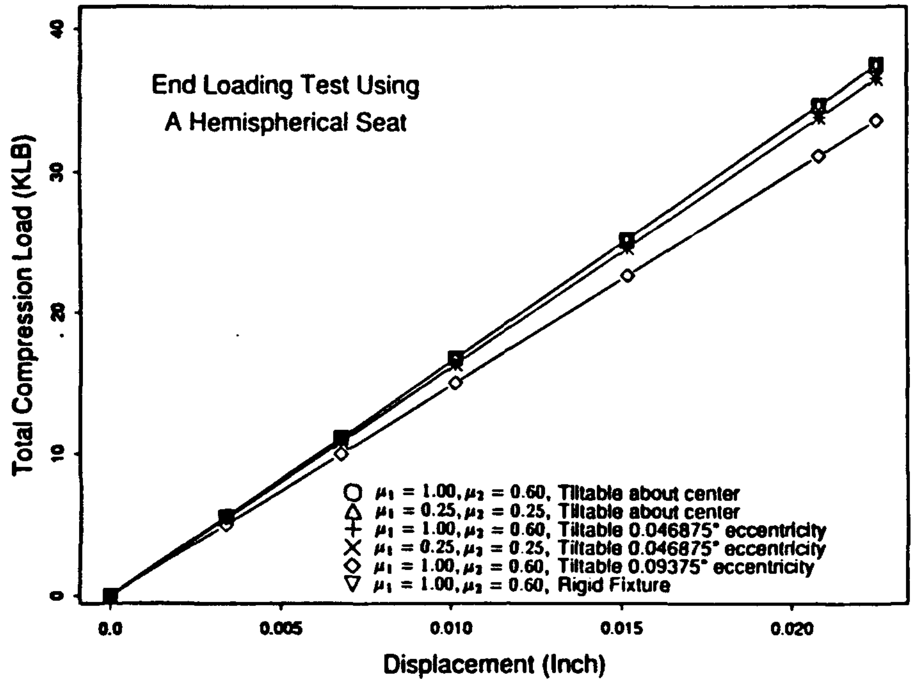
RESULTS OF SIMULATION

Effects of Loading Eccentricity Using a Hemispherical Seat

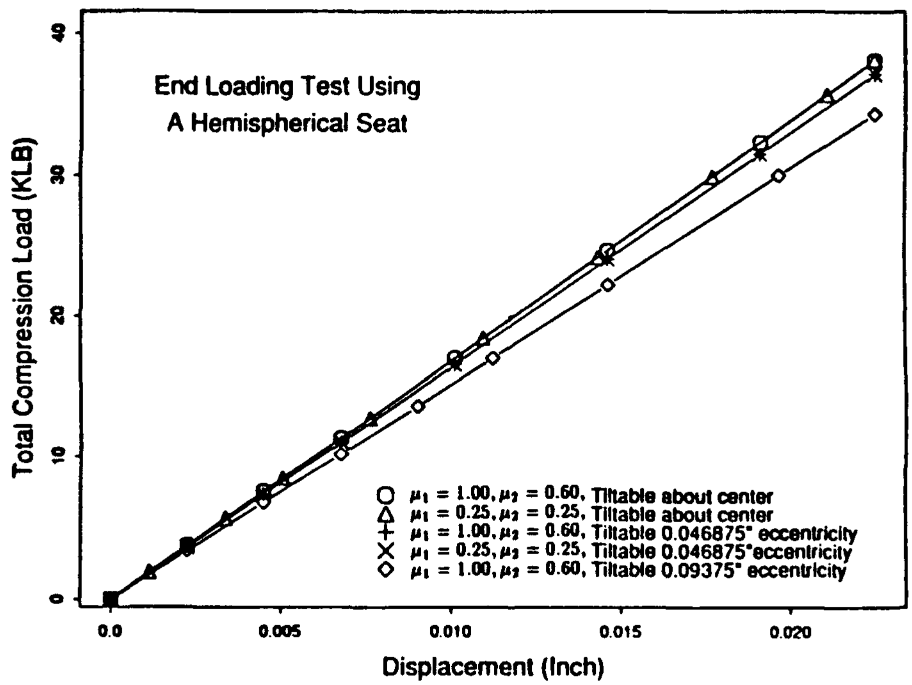
The load-displacement curves of the composite and isotropic materials for different combinations of eccentricities and friction coefficients are shown in Figures 2a and 2b. In the figures, μ_1 and μ_2 are the coefficients of friction at the top and bottom of the specimen. The eccentricities (see Figure 1a) were assumed to vary from 0" to 0.09375". The displacement measured at the top of the specimen is the movement of the crosshead of the machine. The slope of the curve is related to the measured Young's modulus by a constant (specimen length/cross section area).

In Figures 2a and 2b, the moduli are smaller when the loading eccentricity exists. This is the result of the nonuniform deformation and rigid body displacement of the specimen which occurs when the seat tilts. Results from the analysis for the composite specimen showed a tilt angle of 1.4^{o} for the seat with an eccentricity of 0.09375".

The coefficients of friction between the fixture and specimen were not a significant factor in the global deformation behavior of the specimen (see Figures 2a and 2b). However, for relatively large eccentricity and small coefficients of friction, analytical results showed a substantial slippage of the specimen in the fixture. A more detailed discussion of frictional effects is described in the Effects of the Frictional Forces on an End Loaded Specimen Section.



2a. Composite material



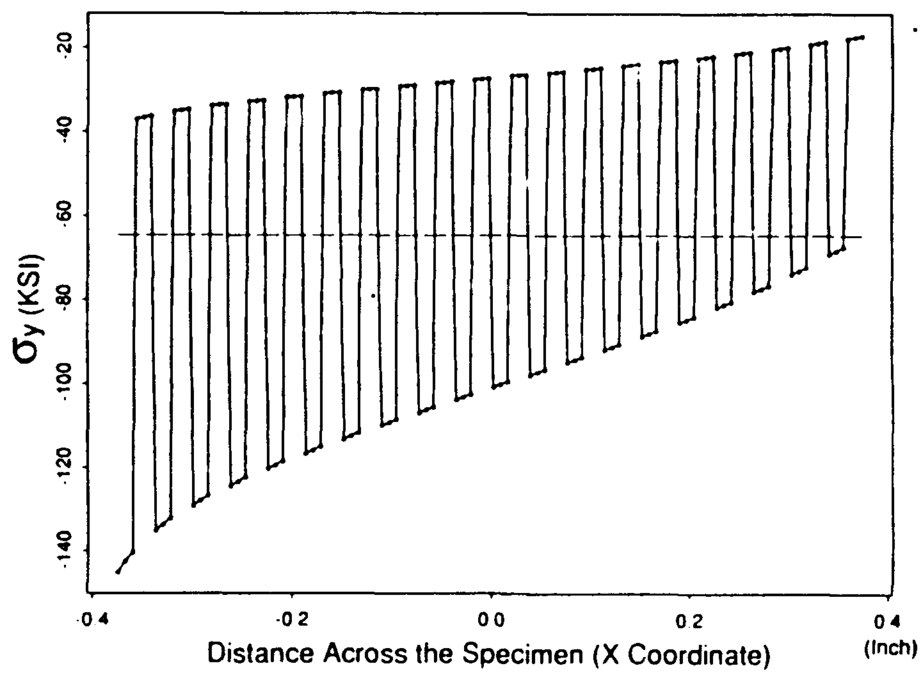
2b. Isotropic material

Figure 2. Load versus end displacement for end loading test using a hemispherical seat.

The stress distribution σ_y along the horizontal cross section near the bottom of the specimen with eccentricities of 0.046875" and 0.09375" are shown in Figures 3a and 3b, respectively. The stress values were obtained from a load corresponding to a displacement of 0.0225" (the engineering strain ε = 1.5%). The oscillating behavior of the stress distribution in Figure 3 is the result of the different orientations (0^o versus 90^o) of the laminas. The higher compression stresses correspond to the stiffer 0^o laminas. The lower compression stresses represent the 90^o lamina results. Comparing the stress values along the specimen cross section for a lamina with the same orientation (0^o versus 0^o, 90^o versus 90^o) shows the differences increase substantially as the eccentricity values are increased. Maximum differences of 75 ksi and 150 ksi for 0^o lamina are shown in Figures 3a and 3b (larger eccentricity). This is the result of the hemispherical seat tilting due to eccentricity. A locked seat can prevent this eccentricity effect.

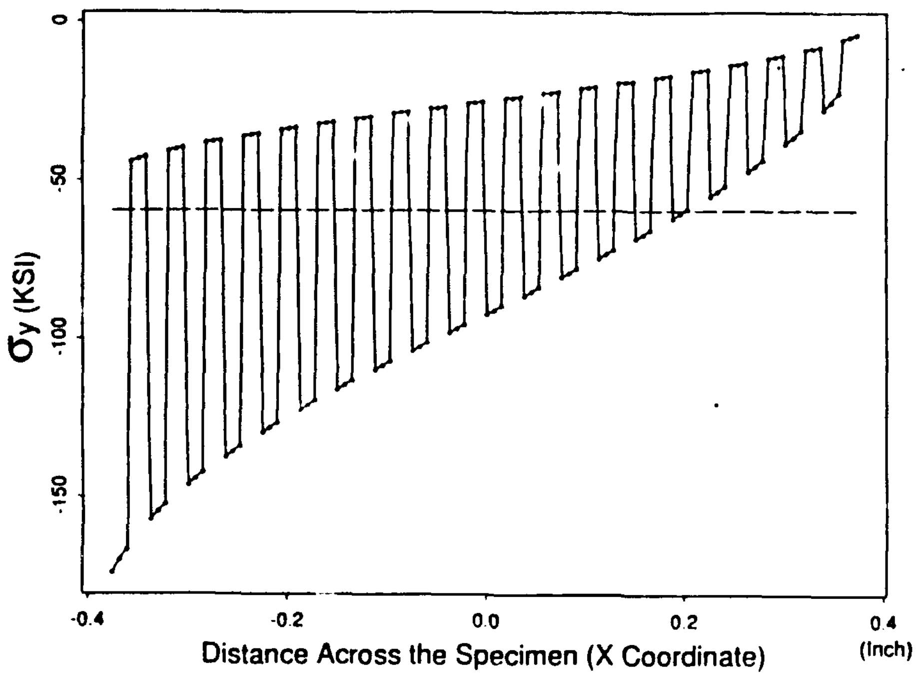
The horizontal dash lines in the figures represent the engineering stresses (load/area). The engineering stress is smaller in Figure 3b since the load for large eccentricity condition is smaller than that for the small eccentricity (see Figures 2). In an ideal condition the stresses in the identical laminas (90^o and 0^o) are the same and the engineering stress is the average between the stresses. The actual stresses become nonuniform for conditions such as eccentricity or imperfection of specimen shape (see the Effects of the Imperfection in the Specimen Geometry Section). The direct relationship between the engineering and actual stresses no longer exists.

The modulus as a function of eccentricity for both composite and isotropic materials is shown in Figure 4a. The modulus values decrease as the eccentricity is increased and the variation of the modulus for the composite material is similar to that of the isotropic material.



3a. 046875" eccentricity

Figure 3. Stress (σ_y) at specimen bottom using a hemispherical seat.



3b. 0.09375" eccentricity

Figure 3. Stress (σ_y) at specimen bottom using a hemispherical seat.

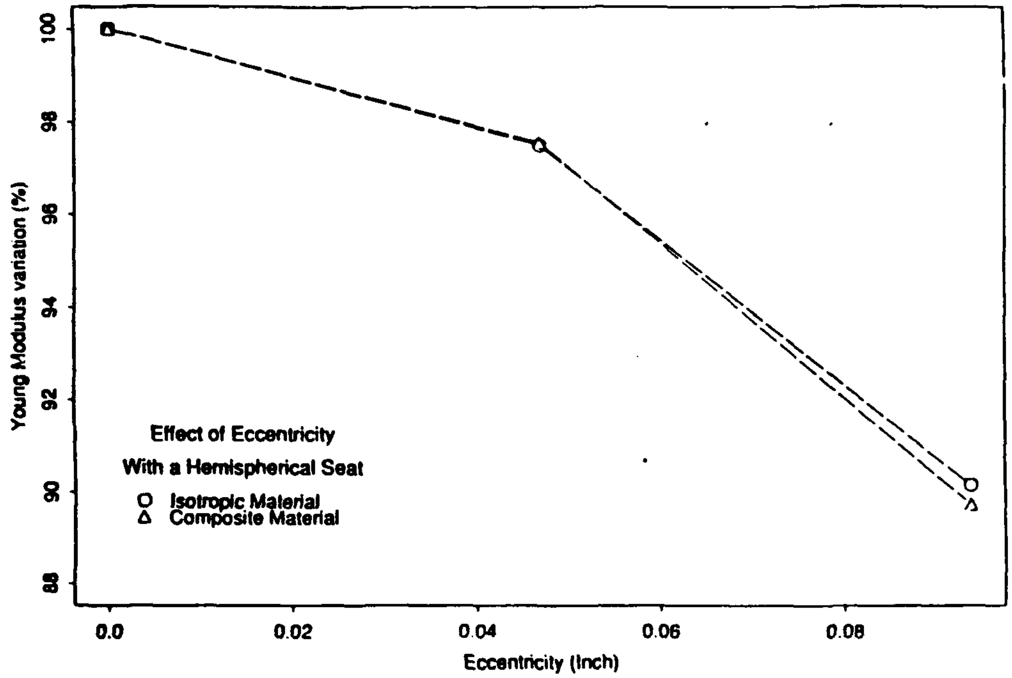
Figure 4b shows the ratio of the maximum and minimum compressive stress versus eccentricity. The stress ratios are approximately 2.2 for both the composite and isotropic material when the eccentricity is 0.046875". When the eccentricity is increased to 0.09375", the stress ratios in the 0°, 90° laminas and the isotropic material become 7.8, 11.7, and 9.2, respectively. This indicates that compression testing of composite materials can be more sensitive to eccentricity when compared to the isotropic material.

The stress ratio in Figure 4b is close to 1 when eccentricity does not exist. This means that the unsymmetric laminate did not introduce significant tilt effect on the hemispherical seat since the following factors contributing to the bending moment are relatively small for this specimen:

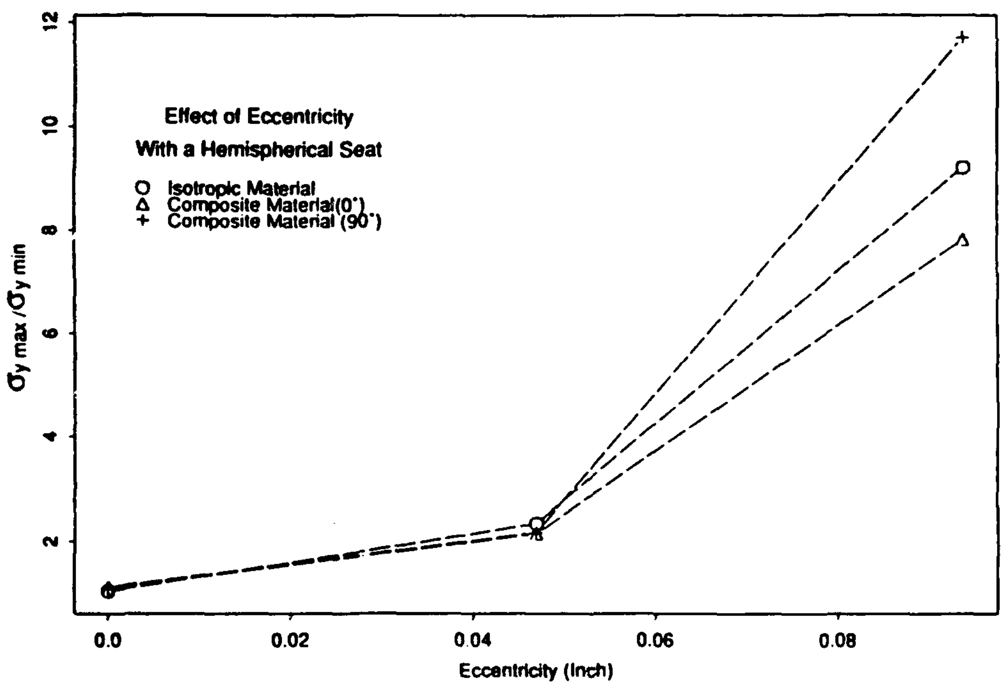
- The lamina thickness is very small compared to the thickness of the specimen.
- The material is not highly anisotropic and the stacking sequence of the laminate is relatively symmetric.

In Figure 4c, a contour plot of the compressive stress distribution (σ_y) of the specimen's 0° laminas* is shown for an eccentricity of 0.09375". The compressive stress across the bottom of the specimen increases from right to left, while the stress at the top is nearly uniform. The nonuniform stress resulted from the tilting of the seat, therefore, the uniform stress region cannot be predicted based upon the Saint-Venant principle.

*The stress variation between 0° and 90° laminas is greater than the stress variation due to the eccentricity, in order to present the effect of the eccentricity only the stress values in the 0° laminas are shown.

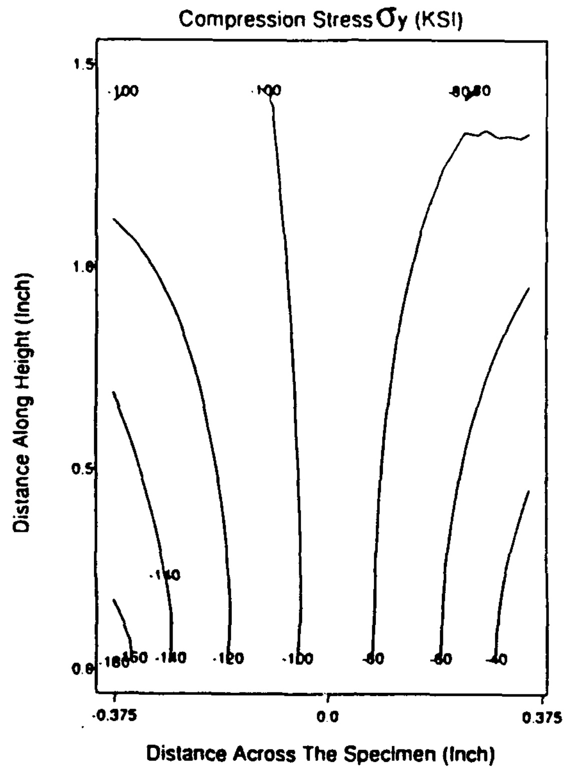


4a. Young's modulus variation versus loading eccentricity



4b. The ratio of the maximum and minimum stress (σ_y) versus loading eccentricity at the bottom of the specimen

Figure 4. The effects of eccentricity in a specimen with a hemispherical seat.



4c. The stress contour plot for 0° laminas of composite material using hemispherical seat with 0.09375" eccentricity

Figure 4. The effects of eccentricity in a specimen with a hemispherical seat.

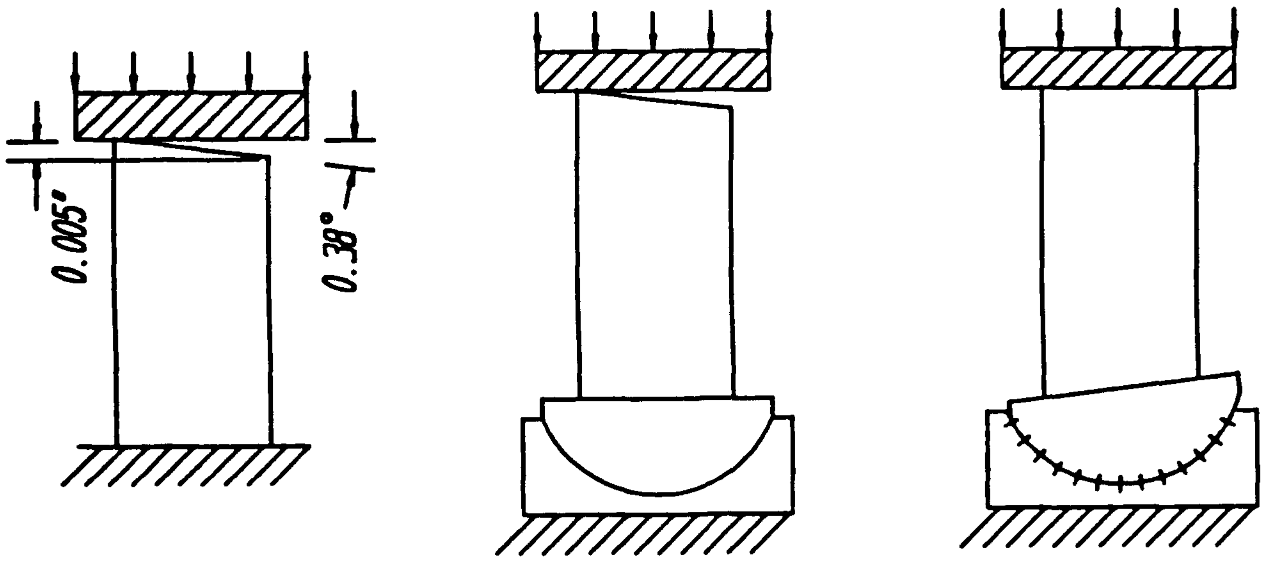
As was previously shown, the modulus (global compression results) is not significantly affected by the loading eccentricity although the nonuniformity of the stress distributions is substantial. This stress distribution can result in a local deformation and an inaccurate measurement of the strength.

Effects of the Imperfection in the Specimen Geometry

Geometrical imperfection of the specimen ends (nonparallel to the fixture) can introduce a nonuniform stress state. In the analysis, a small angle (0.38°) between the specimen end and loading surface is initially assembled (see Figure 5a). Three different cases for the end loading method have been analyzed and are listed as follows:

- An imperfect specimen is loaded by a perfectly rigid fixture (see Figure 5a).
- An imperfect specimen is loaded by a hemispherical seat (see Figure 5b).
- An imperfect specimen is loaded by a hemispherical seat which is locked in place after self-alignment (see Figure 5c).

Figure 6 shows the compressive load versus end displacement results. Figure 7 shows the compressive stress σ_y along the specimen's cross section. In order to demonstrate the effects of specimen imperfection, only the stresses in the 0° laminas are plotted.



5a. Imperfect specimen with rigid fixture

5b. Imperfect specimen with hemispherical seat

5c. Imperfect specimen with a hemispherical seat where the seat is locked inplace after self-alignment

Figure 5. Sketch of the simulations for specimen imperfection.

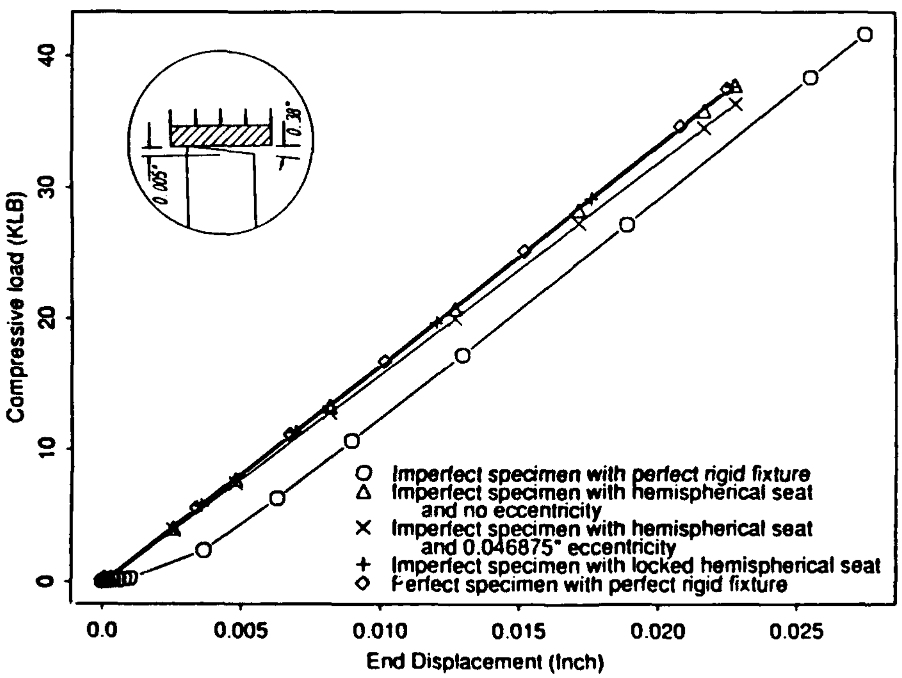


Figure 6. Compressive load versus end displacement for the specimen imperfection.

In Case 1, the results show that the modulus is small initially but gradually increases and becomes equal to the moduli of the other specimen (see Figure 6). The smaller modulus corresponds to the deformation at the imperfect end. When the end becomes parallel to the fixture after a small load, the modulus becomes equal to that of the perfect specimen. In Figure 7, the stress distribution for the Case 1 shows a relative large variation. The maximum stress is 43 ksi larger than the minimum stress. This can result in premature failure of the specimen in the highly stressed region.

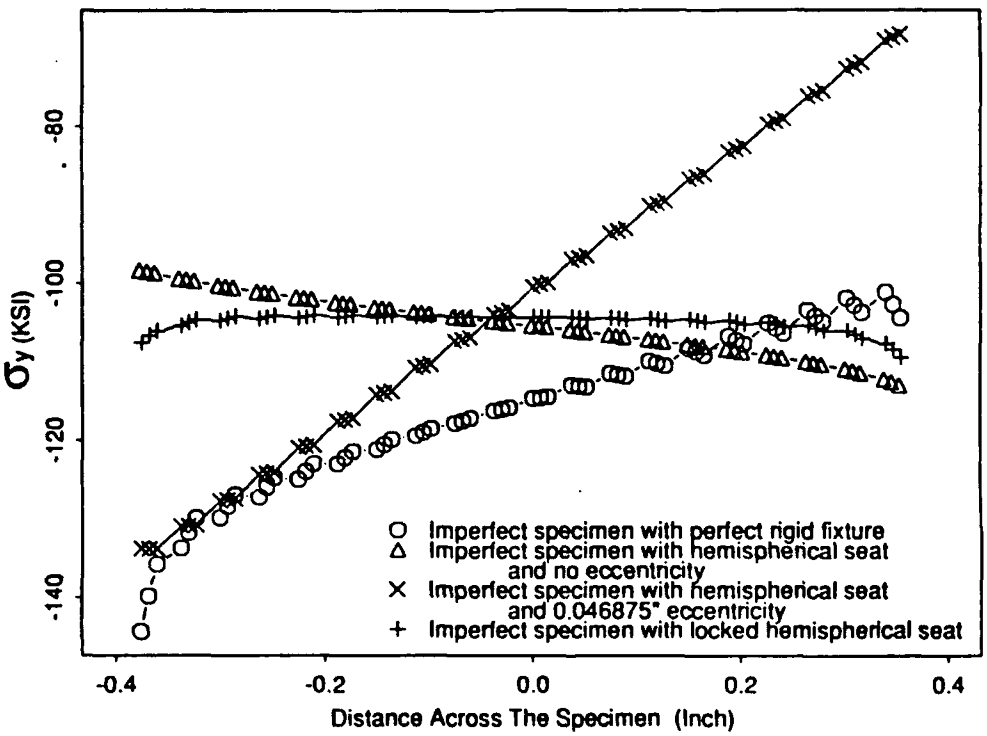


Figure 7. Compressive stress (σ_y) in the 0° laminas of the composite material for specimen imperfection.

In Case 2, the load versus displacement curve (see Figure 6) is similar to the perfect specimen. In Figure 7, the variation of the stress along the specimen's cross section is relatively small. This is the result of using the hemispherical seat which provides uniform contact (self-alignment).

However, as mentioned in the previous section, if there is a small amount of eccentricity the hemispherical seat will tilt and, thereby, introducing a significant change in the stress distribution. A substantial variability of the stress distribution is shown in Figure 7 for the imperfect specimen loaded by a hemispherical seat with 0.046875" eccentricity. Since the nonuniform stress distribution can introduce local deformation, the measured strength in this case will be lower than the actual material strength.

In the Case 3 analysis, after alignment of the specimen, the seat is locked in place before introducing the loading. The seat is now parallel to the specimen end, thereby, the stress variations shown in the previous Case 1 results are removed (see Figure 7). Locking the seat before loading has removed the problem of seat tilt.

The results of this section have shown that a specimen with relatively small imperfections (0.38° inclined end) and loaded by a rigid fixture can introduce considerable measurement errors. The measured modulus which depends on the load on the specimen may be affected slightly. The measured strength which depends primarily on the maximum stress may change substantially, since the specimen which is subjected to nonuniform stress can fail prematurely and there is no correlation between the engineering and the maximum stress. Using the hemispherical seat will reduce the stress concentration due to the specimen imperfection. It is also necessary to lock the seat to prevent the tilt during the loading.

The Effects of the Frictional Forces on an End Loaded Specimen

Large frictional forces between the specimen and the fixture can result in barreling of a metallic specimen. The nonuniform stress resulting from the shape distortion can also cause a reduction in the measured strength.

In contrast, the large frictional forces applied to a composite specimen can provide a more accurate strength measurement. These frictional forces can constrain the surface laminas and the fibers thereby reducing the possibility of local buckling, delamination, and specimen splitting.[6] The barreling of the composite specimen is limited because the total compression strain is small; therefore, the nonuniform stress due to the shape distortion can be ignored.

Figure 8 shows the transverse constrained stress σ_x along the specimen loading axis (Y axis) for different coefficients of friction. The larger coefficient of friction can result in higher constrained stress value at the specimen ends. The constrained stresses only affect the end region of the specimen and become zero at the middle.

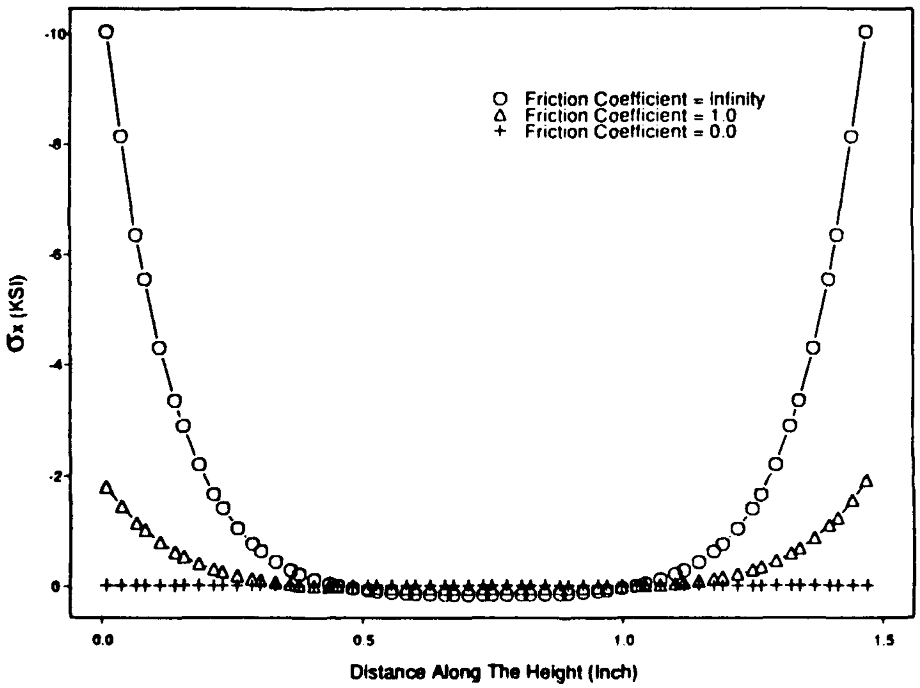


Figure 8. Constrained stress (σ_x) along the specimen height (Y coordinate) with different coefficients of friction.

The modulus measurement is only slightly affected by the frictional forces since the slopes of the curves, as shown in Figure 2a, did not change with the coefficient of friction. The results of analysis also showed that the distribution of compression stresses σ_y are similar for different coefficients of friction.

Determination of the End Effects for Different Loading Methods

The Saint-Venant principle is very useful criteria in determining the end zone when applied to either experimental or analytical engineering problems. In compression testing, an end zone is defined as a region where the end effects cannot be neglected.

The end zone of an anisotropic material can be much larger than that of the isotropic material. In a review paper on the Saint-Venant principle,[5] it was shown that for an anisotropic material under plane deformations, the estimated size of the end zone (λ) depends on the ratio of longitudinal Young's modulus E_L and transverse shear modulus G_{LT}. The estimated zone size was approximately eight times the width (or thickness) of the specimen for a high strength fiber composite material with $E_L/G_{LT} = 125$. This zone was also eight times greater than that of an isotropic material.

Both end loading and side loading tests were analyzed using high strength fiber 0^o composite and isotropic materials. The normalized stress $\sigma_y/\bar{\sigma}_y$ as function of the ratio of height to thickness of the specimen is shown in Figure 9 where the $\bar{\sigma}_y$ is the engineering stress value.

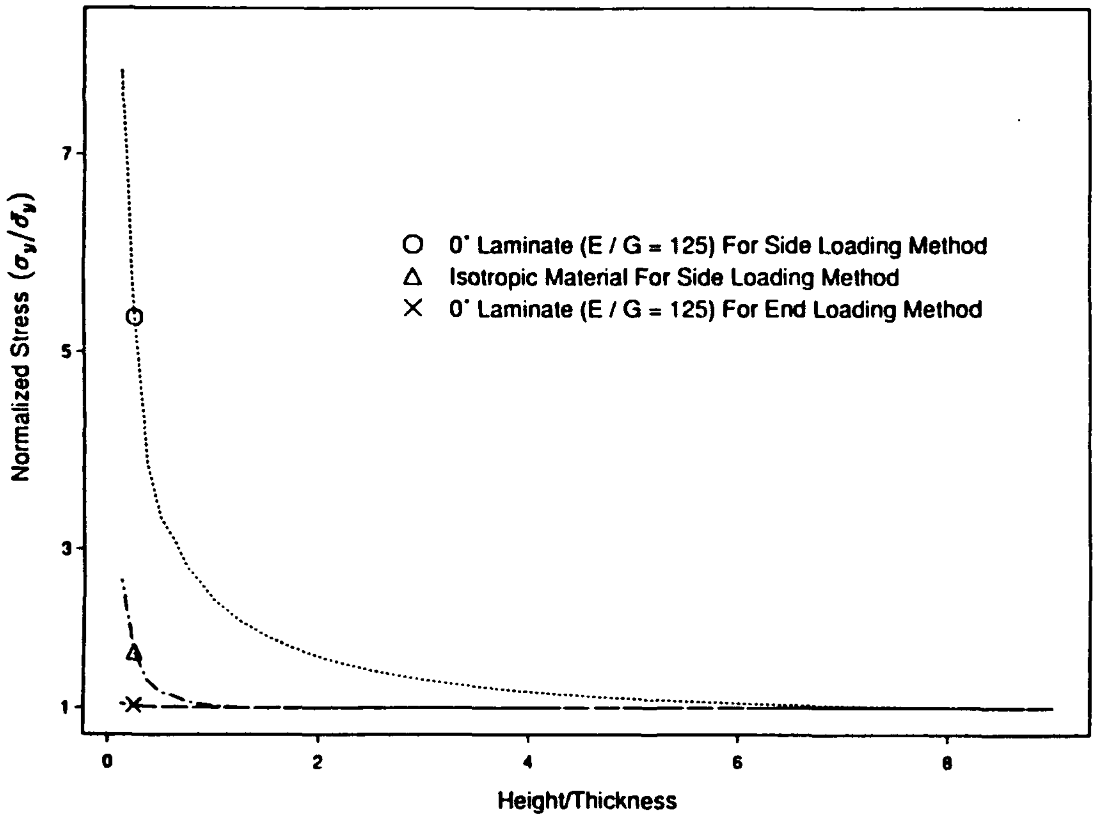


Figure 9. End effects on stress distribution.

In the end loading method, the load applied on the specimen end is the required load, therefore, the size of the end zone for compression stress σ_y is negligible for both materials. The normalized stress is close to 1.0 at the end (height to thickness ratio equals 0) of the specimen (see Figure 9).

In the side loading method, the surface shear load is transferred to the compression load, therefore, the end zone is much greater than that of the end loaded specimen. Isotropic and composite material end zones are one and eight times that of the thickness when the end zone is defined as a region which has 1% deviation in the uniform stress (see Figure 9). These results are similar to those obtained from Horgan.[5]

The end effects for the highly anisotropic materials cause two problems in the side loading method; first, a large gage length is required which increases the chances of buckling and, secondly, the high stress concentration at the loading end can cause the failure in that region (see Figure 9 and Reference 3).

EVALUATION

Evaluations of the analytical results for compressive test methods are summarized as follows:

- A specimen, with relative small imperfections, loaded by a rigid fixture can be subjected to nonuniform stress.
- Testing errors due to the specimen imperfections can be eliminated if a lubricated hemispherical seat is placed under the specimen. This allows the seat to rotate parallel to the specimen contact surface.
- The eccentricity between the specimen and the load axis can introduce significantly large stresses variation in the specimen when the hemispherical seat is tilted during the testing process.
- Locking the hemispherical seat in place after self-alignment and before conducting the compression test will prevent the tilting of the seat thereby avoiding potentially large stresses variation.
- In end loading, the large frictional forces between the specimen and the machine crosshead tend to prevent the local failure at the ends of the specimen thereby providing a more accurate measurement of the strength.
- The end effect on the composite material is insignificant when the end loading method is used. Applying the side loading method to composite material results in a much larger end effect than that for isotropic material.

These evaluations are based only upon the present simulation results, therefore, experimentation is suggested in order to verify the analytical results presented in this paper.

CONCLUSIONS

A finite element model has been used to evaluate compression test methods for thick-section composite materials. An end loaded specimen supported by a locked hemispherical seat was determined to be the most desirable than the side loading method for the thick composite since it provided uniform stress field in the specimen. The locked hemispherical seat

eliminates the stress concentration due to specimen imperfection while providing the necessary support for the specimen by preventing a tilt action due to eccentricity. Constraining the specimen ends with frictional forces can prevent local failure, therefore, a more accurate strength measurement may be obtained.

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2	ATTN: SLCMT-TML
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An improved compression test concept for thick-section composite materials based on a stress analysis simulation study is presented. An end loading method involving specimen support by a locked hemispherical seat was identified as the most desirable. The results showed that this method could substantially reduce the stress variation due to specimen imperfection and loading eccentricity. Compression test methods are analyzed using a finite element methodology. Limitations of the test methods are identified with respect to their ability to obtain the desired uniform stress field. The end loading method proved to be superior to the side loading method for the thick-section composite material. The frictional forces introduced by the end loading method can reduce local failure at the specimen end. The zone of end effects on the stress distribution was obtained for the composite material.

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